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# Generation and Characterization of low-charge electron beams at the NML Facility with Applications to next Generation X-ray free-electron lasers

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Philippe Piot (Fermilab),  
John Power (Argonne)*

Uchi-ANL-FNAL collaboration meeting  
December 7th, 2010

# Our ANL-FNAL-Uchi collaboration



## Argonne:

**APS:** extensive beam simulation tools, light source R&D

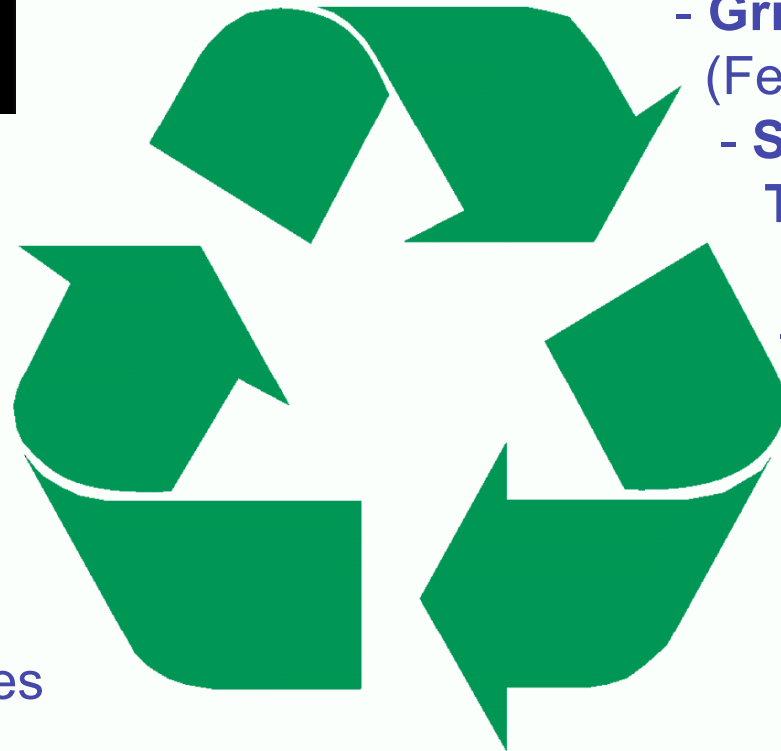
## Argonne Wakefield Accelerator:

- test facility available for experiments
- expertise in e- sources and instrumentation



## U. Of Chicago (Physics)

KJK's group: expertise in **accelerator-based light source**  
**Muon collider physics, students**



## Fermilab:

- **Grid computing** (FermiGrid)
- **Superconducting Test Accelerator Facility (STF@NML)**
- **A0 Photoinjector Test Facility**  
Diagnostics R&D  
laser development



# Collaborators

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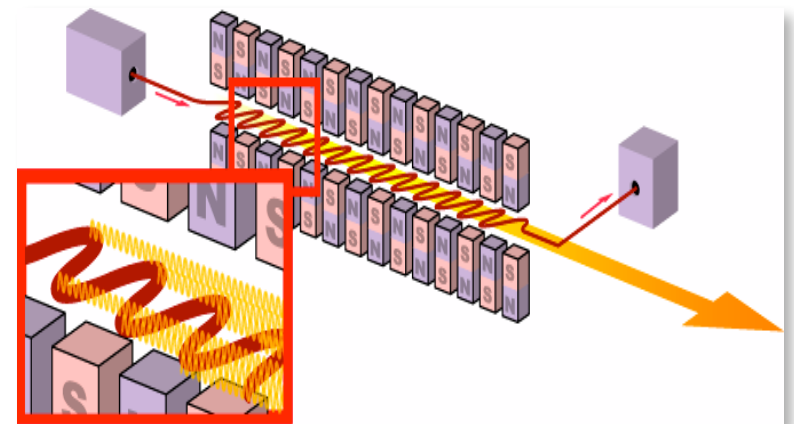
- **Uchi:** K.-J. Kim, G. T. Park<sup>#</sup>, and A. Valkovich<sup>#</sup>.
- **ANL:** J. Power,
  - Laser R&D and Instrumentation: J. Power,
  - Simulations: M. Borland and H. Shang (provide `Elegant` and `GeneticOptimizer`), L. Emery (provided/modified `Shower`),
- **FNAL:** P. Piot,
  - M. Church (STF@NML facility manager),
  - Simulations: C. Prokop<sup>#</sup>, Y.-E Sun\*, J.C. Thangaraj\*,
  - Laser R&D: J. Ruan,
  - Instrumentation: A. Lumpkin, J. Ruan.

\* Fermilab Peoples fellows

<sup>#</sup> Graduate student from Northern Illinois University (sponsored by Los Alamos National Lab.)

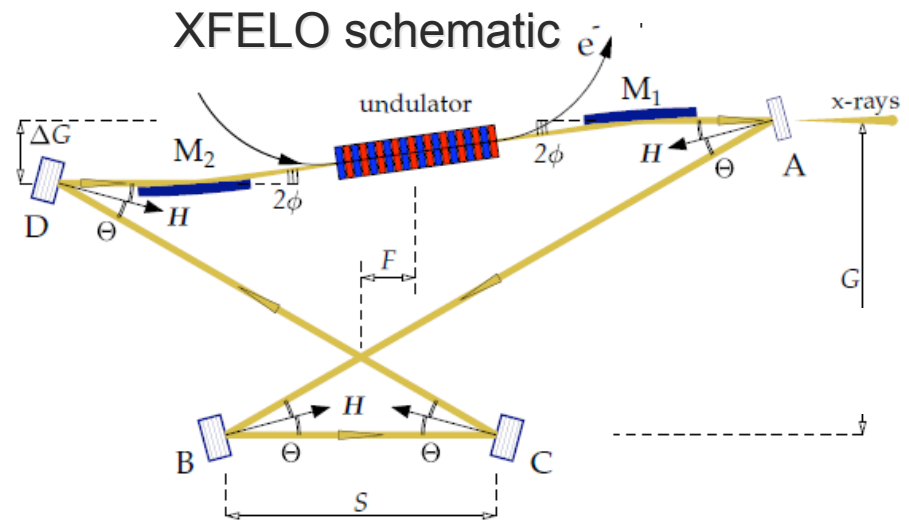
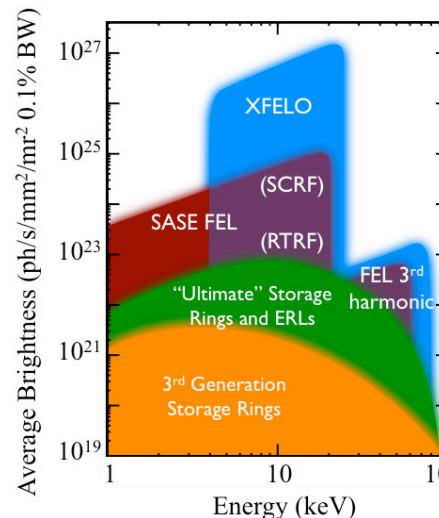
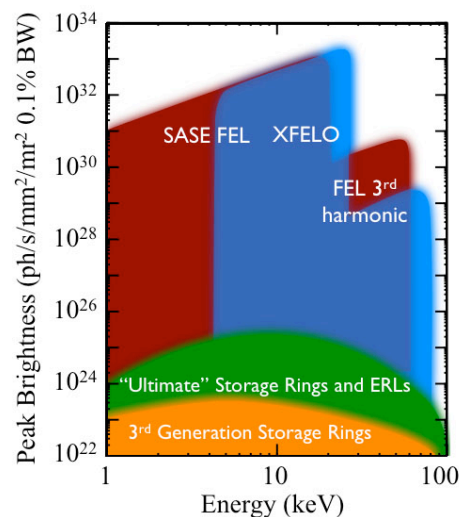
# Introduction

- Accelerator-based light sources using the free-electron laser (FEL) principle have opened new research opportunities,
- These light sources have unique properties (tunability, coherence, peak E-field) and enables, e.g., the exploration of dynamical process in biology, chemistry, material science,
- **Recent developments**
  - “Single-spike” single-pass FELs: can provide ultrashort (10-fs) x-ray pulses,
  - “X-rays FEL oscillators” can produce narrow-band fully-coherent hard x-rays.
- The performances of FEL-based light sources are strongly correlated to the properties of the driving electron beams



# X-ray FEL oscillator (XFEL0)

- Opens a new avenue for the future hard x-ray science
- Fully coherent, tunable hard x-rays,  $\sim 1$  meV bandwidth,  $10^9$  photons/pulse, 1 MHz repetition rate
- XFELs will dramatically improve techniques developed in the 3<sup>rd</sup> generation light sources and will create new opportunities complementary to single-pass FELs



K.-J. Kim et al., PRL 100, 244802 (2008)

Uses diamond crystals with a high Bragg reflectivity

# Requirements on electron beams

- These accelerator-based light source put stringent requirement on the *brightness* of the electron beams
- In Beam Physics, the brightness is defined in term of canonical *emittances*, e.g.,

$$\varepsilon_x = \frac{1}{m_e c} \left[ \langle x^2 \rangle \langle p_x^2 \rangle - \langle x p_x \rangle^2 \right]^{1/2} \geq \frac{\hbar}{2m_e c}$$

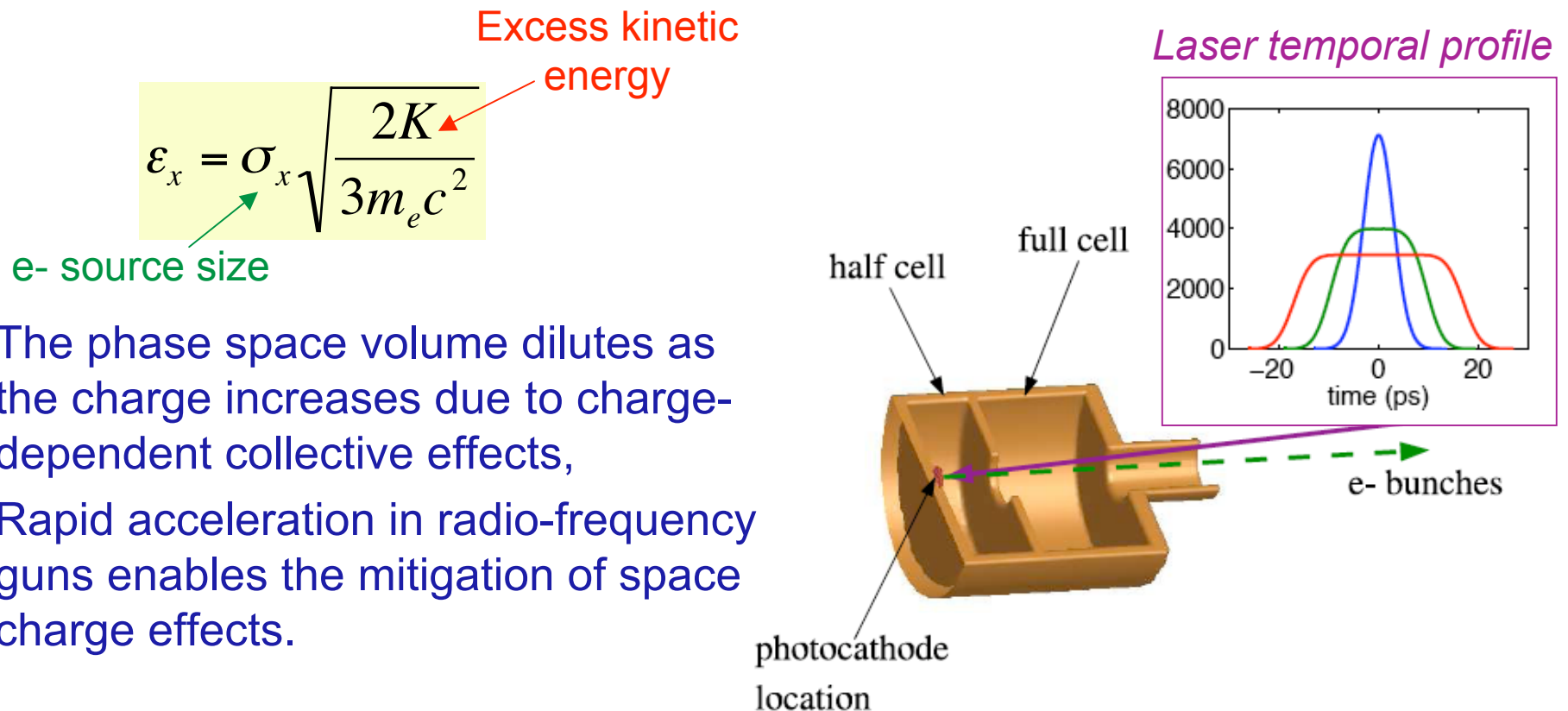
for the phase space associated to the horizontal  $(x, p_x)$  degree of freedom.

⇒ *high brightness* is a compromise between *low emittances* and *high charges* which are antagonist requirements...

The diagram shows the formula  $B = \frac{Q}{\Gamma} \propto \frac{Q}{\varepsilon_x \varepsilon_y \varepsilon_z}$ . Annotations include: a green arrow pointing to 'charge' for  $Q$ ; a red arrow pointing to 'phase space volume' for  $\Gamma$ ; and three blue arrows pointing to 'emittances' for  $\varepsilon_x, \varepsilon_y, \varepsilon_z$ .

# Challenges in producing “bright” e- beams

- Ultimately, the achievable brightness is limited by the electron emission process. In particular the transverse emittance is fundamentally limited to

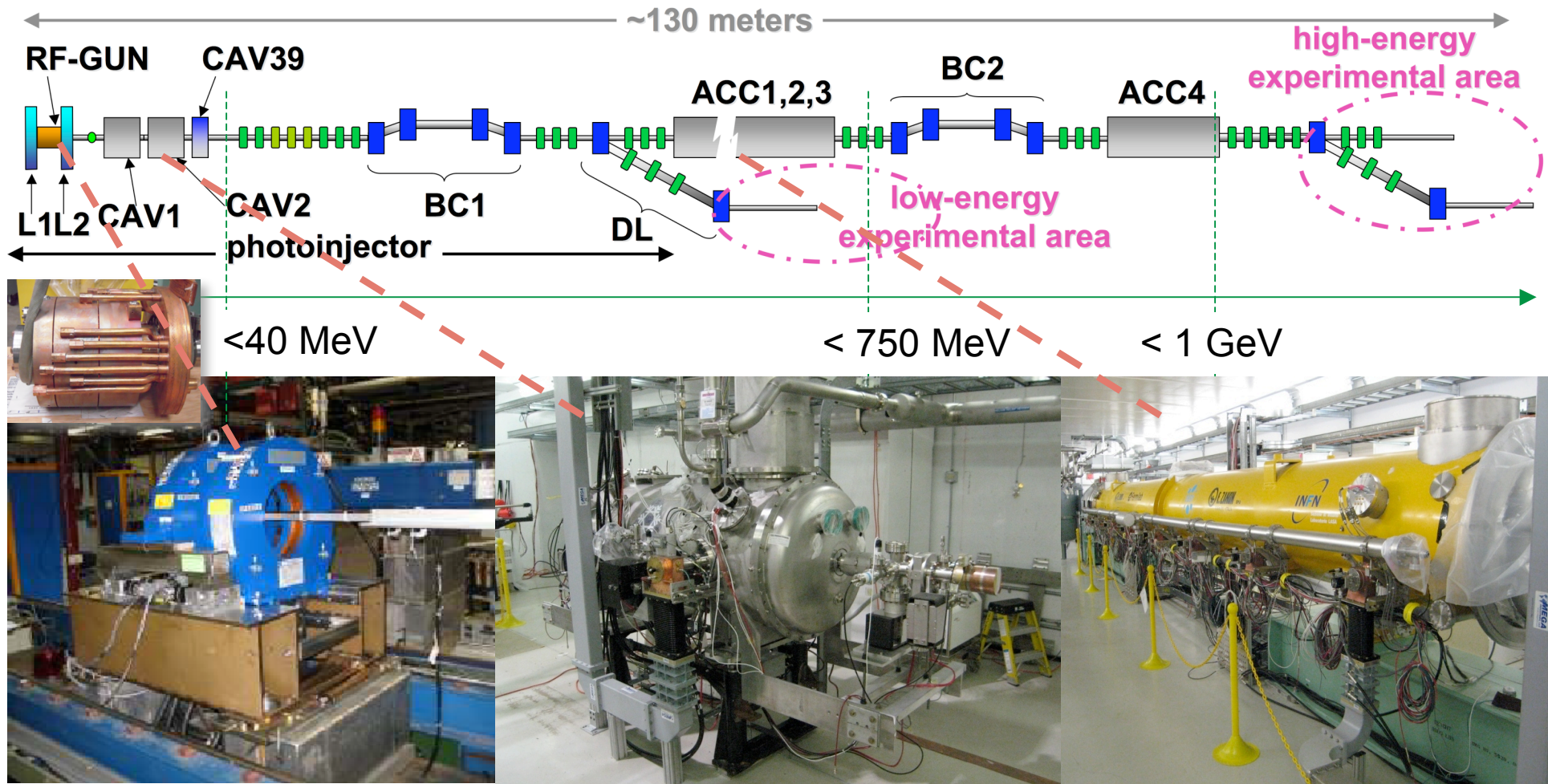


- The phase space volume dilutes as the charge increases due to charge-dependent collective effects,
- Rapid acceleration in radio-frequency guns enables the mitigation of space charge effects.
- Producing a beam with low current reduces collective effects and enables the operation with electron source size ( $\sigma_x$ )  $\Rightarrow$  low emittances.



# The STF@NML facility at Fermilab

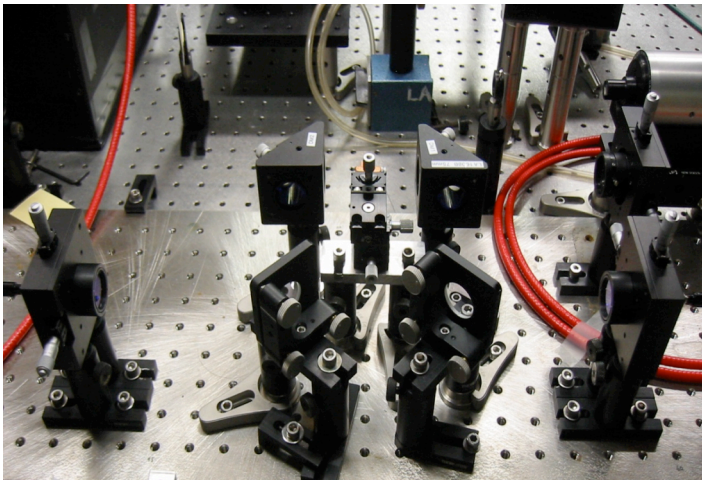
- Fermilab is constructing a superconducting accelerator test facility (STF)
- The facility will be capable of producing bright electron beams.



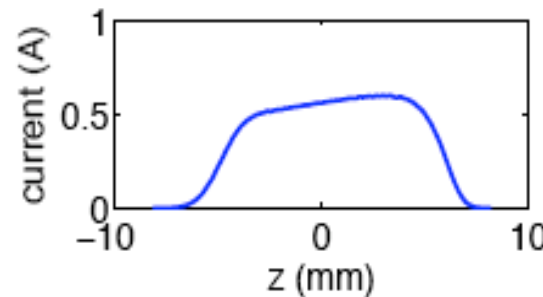


# High-brightness beams at STF@NML

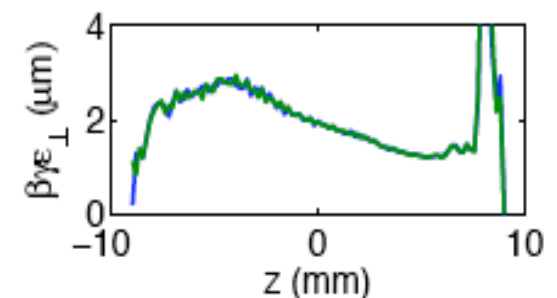
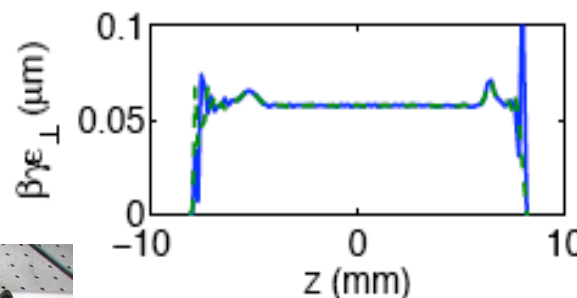
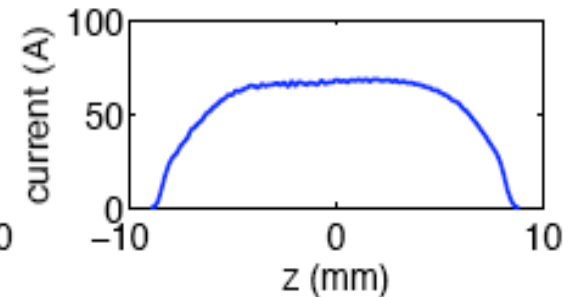
- Simulations of the 40-MeV photoinjector indicate that low-emittance beams can be obtained at low charges
- This is achieved with a conventional photoemission source with a long flat-top laser



Q=20 pC (low charge)



Q=3.2 nC (ILC)

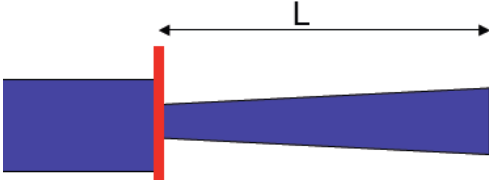


- developing a pulse stacker to produce such laser pulse present several challenges: flatness, density modulation, ...

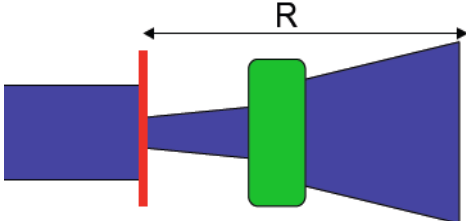
# Challenges in measuring “bright” e- beams

- Measuring low emittances at low energies is challenging and can be severely limited by resolution issues

Standard technique


$$\sigma_x = \sqrt{\frac{w^2}{12} + L^2 \sigma_x'^2}$$

Improved technique


$$\sigma_x = \sqrt{R_{11}^2 \frac{w^2}{12} + R_{12}^2 \sigma_x'^2}$$

- The A0 photoinjector has transverse emittances  $\varepsilon \sim 1 \mu\text{m}$  comparable to the resolution limit of the present diagnostics
- We are developing an improved technique with enhanced resolution
  - Simulation in progress (there is a limit on tolerable fractional energy spread)
  - The technique will be experimentally tested next year at the A0 photoinjector

# Status

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- Laser R&D
  - Commissioning a new streak camera at the A0 photoinjector
  - Laser part to enable the generation of long flat-top pulse will be specified and procured once the STF@NML laser oscillator is back from factory
- Beam dynamics simulations
  - Start-to-end simulation of NML are in progress and will be used to assess the acceleration and compression of 1-GeV ultra-low emittance beams
- Diagnostics R&D
  - Numerical modeling of an improved emittance diagnostics is underway
  - Experimental test planned in Feb. 2011.

Thank you for your support!